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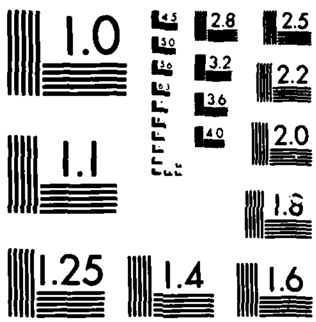

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number):

Planar technology for millimeter-wave circuits has been studied. Coplanar waveguide filters have been developed. A fully planar monolithic 35-GHz oscillator and a planar 70-GHz receiver have been built.

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RESEARCH ON DEVICES FOR INTEGRATED MILLIMETER WAVE SYSTEMS

S. E. Schwarz

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18 June 1979 - 31 Jul 85

U. S. ARMY RESEARCH OFFICE

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This program deals with development of millimeter-wave integrated circuits and related technology. A great deal of progress has been made over the period of this report. Beginning with simple components such as antennas and waveguides, we have advanced to more complicated devices such as filters and to active devices, including the first monolithic millimeter-wave oscillator.

Initially, planar antennas were studied. [1] The fundamental problems of such antennas were identified, the principal one being that of radiation into guided substrate modes. Two practical planar antennas were suggested, the "sandwich-V" antenna and the tapered dielectric rod. Since then, several other antennas suitable for inclusion in planar circuits have been studied. These include the "Vivaldi" antenna, the bow-tie, and the multiple slot array.

It was important to demonstrate that these planar antennas could be integrated with other components to form planar systems. The first demonstration was in the form of a planar array of bolometer detectors equipped with a planar grid antenna structure.[2] This device was in effect a large area power sensor. However the grid antenna was unsuitable for use with individual detectors or receivers. Thus we proceeded to integrate the dielectric rod antenna with a Schottky diode to form a primitive integrated receiver. [3] This device was built in silicon, and demonstrated that dielectric waveguide could be coupled to diodes with coupling loss on the order of 1.5 dB.

The use of dielectric waveguide for millimeter waves was investigated further. [4] In particular, the type known as "ridge" waveguide was studied in detail. This form of dielectric waveguide is interesting because it is built on a dielectric "web" which can also form the substrate for semiconductor devices. The properties of ridge guide of various dimensions were studied in detail.

Dielectric waveguide is useful at the higher millimeter-wave frequencies because dielectric loss per guide wavelength is constant as frequency increases.

On the other hand, the ohmic loss of metallic waveguide increases with frequency owing to skin effect. However, dielectric waveguide has the liability of a 1.5-dB coupling loss whenever power must be transferred to a semiconductor device. Consequently there exists a "cutoff frequency", above which it pays to use dielectric waveguide; below the cutoff frequency, metallic waveguide is adequate. Our work indicates that the cutoff frequency is in the range 50-100 GHz. Since present applications are concentrated below 100 GHz, we confined further efforts to metallic transmission structures. In particular, we have emphasized the use of coplanar waveguide (CPW). The advantage of CPW, as compared, for example, with microstrip, is that circuit elements can be connected in shunt as well as in series. Furthermore it is more truly planar than microstrip, thus lending itself more readily to planar fabrication techniques. Also its transmission properties are less dependent on substrate thickness than are those of microstrip, and thicker substrates can be used. The principal drawback of CPW is its slightly higher ohmic loss.

Clearly it is desirable to construct oscillators in planar form. Such oscillators would be compatible with small planar receivers, and large versions might also be used in transmitting applications. The resonator of such an oscillator would be a short-circuited section of transmission line on the surface of the substrate, and a negative-resistance diode at its input terminals would complete the circuit. The evident problem with such a device is radiation from the open resonator, which would lower its Q until oscillation might not be obtained. Coplanar waveguide is especially well-suited for such a resonator, because its balanced form tends to minimize radiation. We began with large- scale modeling of the resonator. These models were combined with ordinary encapsulated Gunn diodes, in order to demonstrate that the oscillator with open resonator would be expected to work. [5]

We then proceeded to fabricate an actual 35-GHz oscillator based on the preceding design. In this device a surface-oriented Gunn diode was used, with the resonator, a short-circuited coplanar waveguide, built monolithically on the same substrate. [6] Oscillation was obtained, with output power in the 3-5 milliwatt range. This device is to our knowledge the first (and still the only) monolithic millimeter-wave oscillator that has been reported.

Several further developments of the monolithic oscillator were attempted. The greatest amount of effort was expended in trying to integrate a varactor tuning diode in the oscillator structure. This appears to be feasible, as the necessary epitaxial doping profiles of the two devices are reasonably compatible, but success was not achieved due to the technical difficulties of this fairly complicated GaAs device. It would also be desirable to add a dielectric resonator for frequency stabilization, and some work was done on this. The most interesting further developments, it now seems, lie in the direction of higher output power. One approach would be to replace the Gunn device by an IMPATT diode, which could be done with little modification of the design, aside from the doping profile of the epitaxial substrate. Another approach would be through the use of an array of negative-resistance diodes. One advantage of planar fabrication of diodes is that it lends itself well to arrays. Using an array of diodes would allow us to provide each diode with adequate heat-sinking, and a sizable array would provide increased output power, perhaps approaching one watt. The principal problem here is one of circuit design. Each diode must be provided with the appropriate load impedance, and they must be all made to be oscillate in phase. This can probably be done, and the problem is being pursued.

Two related projects have also received support during the reporting period. One of these involved the development of bandpass filters based on CPW. This is an example of the general development of circuit elements that must take place if CPW is to become as generally useful as microstrip. In our work we

developed design rules for CPW bandpass filters [7], and demonstrated that in spite of being open structures they are reasonably free of radiation loss. Predictable bandwidths and satisfactorily low insertion losses were obtained for several designs. These filters have subsequently been used as components of advanced receivers.

Another project involved the fabrication of receiver arrays for imaging. In this application, integrated technology is used not to combine dissimilar components into a single sophisticated receiver, but rather to construct an array of very simple receivers, each with its own receiving antenna. This work was carried on in collaboration with the group at Cal Tech. [8] Satisfactory results were obtained at 69 and 94 GHz. An interesting finding is that the very simple receivers used in these arrays, consisting essentially of a bow-tie antenna, a mixer diode, and nothing else, have performance not tremendously inferior to that of more sophisticated receivers, having, for example, image enhancement. The improvement provided by image enhancement is only on the order of 1.5 dB in conversion loss. These receiver arrays are potentially useful in imaging applications. However, several problems remain to be solved. A way must be found to extract the information from the i.f. channels of a large array of receivers, and it also must be provided with adequate local oscillator power for all the diodes.

Work is presently continuing under renewed ARO support. We are at this moment emphasizing development of sophisticated planar receivers, as well as the general problem of realizing high-powered millimeter wave oscillators in planar form.

The following publications appeared during the reporting period and acknowledged ARO support:

[1] D. B. Rutledge, S. E. Schwarz, T.-L. Hwang, D. J. Angelakos, K. K. Mei, and S. Yokota, "Antennas and Waveguides for Far-Infrared Integrated Circuits," *IEEE Journal of Quantum Electronics*, vol. QE-16, no. 5, May 1980 pp 508-516.

Abstract - Antennas and waveguides for the wavelength range 0.1-3 mm are considered. Emphasis is placed on those designs which lend themselves to integration with each other and with other components such as diodes. The general properties of FIR antennas are reviewed. A novel silicon waveguide antenna is discussed, and its design, simulation, fabrication, and performance at 119 μm are described. This antenna has a highly symmetrical, single-lobed beam with 3 dB beamwidths of 35 and 38° in the E- and H-planes, respectively. The gain (measured in microwave simulation) is 12.8 dB. This antenna is well suited for integration with Schottky diodes.

The related subject of FIR waveguides is discussed. Experiments with metal transmission lines at 119 μm are described and dielectric guides related to the waveguide antenna are also considered. Using components such as these it may soon be possible to construct receiver front ends for this wavelength range in integrated-circuit form.

[2] D. B. Rutledge and S. E. Schwarz, "Planar Multi-Mode Detector Arrays for Infrared and Millimeter-Wave Applications," *IEEE Journal of Quantum Electronics*, vol. QE-17, no. 3, March 1981, pp. 407-414.

Abstract - A new type of detector array is described. By means of a suitably designed metallic network, many detector elements (each individually small compared to wavelength) are assembled into an impedance-matched termination for radiation incident normally on the plane of the device. Residual reactance is tuned out by means of a movable backshort. An array of 400 bismuth-film microbolometers with a total area of 1 cm^2 has been

tested at 215 GHz. A coupling efficiency of approximately 60 percent was observed. The detector has a D^* of 4×10^8 cm $\cdot$ Hz$^{1/2}$/W at room temperature with response time on the order of 2×10^{-7} s. Similar arrays of Schottky and SIS diodes can probably be constructed.

[3] C. Yao, S. E. Schwarz, and B. J. Blumenstock, "Monolithic Integration of a Dielectric Millimeter-Wave Antenna and Mixer Diode: An Embroyonic Millimeter-Wave IC," *IEEE Trans. Microwave Theory and Techniques*, vol. MTT-30, August 1982, pp. 1241-1247.

Abstract - A monolithic silicon integrated circuit consisting of a mixer diode and an all-dielectric receiving antenna has been built and tested at 85 GHz. Radiation is coupled into the device optically with a coupling loss of 2.7 dB. No external metal structure is required for coupling. The design can be used efficiently at considerably higher frequencies, and can be elaborated into more complex integrated circuits. From measurements of video responsivity the losses of various parts of the device are estimated. A simple theory of conversion efficiency is found to agree well with experiments; this theory is then used to predict the performance of improved versions of the device. The conversion efficiency obtained with this demonstration device is low; it is shown, however, that acceptable conversion efficiencies can be obtained with a more advanced diode fabrication technology using epitaxial Si or GaAs. Integrated millimeter-wave receivers of this kind should be suitable for short-path terrestrial communications, in applications where compactness and low cost are required.

[4] T. Wang and S. E. Schwarz, "Design of Dielectric Ridge Waveguides for Millimeter-Wave Integrated Circuits" *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-31, no. 2, February 1983, pp. 128-134.

Abstract - All-dielectric ridge waveguides may be useful as elements of millimeter- and submillimeter-wave integrated circuits. A planar metallic V-coupler can be used to couple energy between the guide and small circuit elements such as diodes. Desirable characteristics in such a guide/coupler system are: a) quasi-single mode propagation; b) low radiation loss in bends; c) low coupling loss between guide and devices; and d) adequate physical strength. In this paper, we discuss the general problem of designing guides and couplers to obtain the desired characteristics. The principal method used is simulation in the range 2-7 GHz. We find that with good compromise designs, typical coupling loss between waveguide and a small device is about 1.4 dB, exclusive of dielectric loss and ohmic loss in the coupler.

[5] N.-L. Wang and S. E. Schwarz, "Planar Oscillators for Monolithic Integration," *International Journal of Infrared and Millimeter Waves*, vol. 3, no. 6, 1982, pp. 771-782.

Abstract - Planar oscillators for monolithic millimeter-wave integrated circuits are considered, and a design based on a coplanar-waveguide resonator is described. Design data are obtained from simulation at 1 GHz. The resonator has a Q of 195 (50 when scaled to 100 GHz) and is mechanically tunable over a range of 12%. Combining this resonator with a Gunn diode, a model oscillator is obtained. Output is obtained quasi-optically through a transmitting antenna. Twenty one milliwatts of output at 4.5 GHz are obtained with high spectral purity. A 100 GHz monolithic planar oscillator based on this design should be possible.

[6] N. Wang and S. E. Schwarz, "Monolithically Integrated Gunn Oscillator at 35 GHz," *ELectronics Letters* vol. 20, no. 14, July 1984, pp. 603-604.

Abstract - A fully planar monolithically integrated Gunn oscillator for 35

GHz has been constructed on a Ga As substrate. An output power of about 1.5 mW, corresponding to an efficiency of 0.5%, is obtained from the oscillator in its present unoptimized form. The device is intended for use as a local oscillator in integrated millimeter-wave receivers. Measurements are made by means of quasi-optical output coupling.

[7] D. F. Williams and S. E. Schwarz, "Design and Performance of Coplanar Waveguide Bandpass Filters," *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-31, no. 7, July 1983, pp. 558-566.

Abstract - End-coupled resonator bandpass filters built in coplanar waveguide are investigated. The admittance inverter parameters of the coupling gaps between resonant sections are deduced from experiment, and bandpass filter design rules are developed. This allows easy filter synthesis from "prototype" low-pass designs. Measurements of single section resonator quality factors are used to predict filter insertion losses. Several examples of filters realized in coplanar waveguide are presented. Odd-mode coplanar waveguide filter elements that shortcircuit the even coplanar waveguide mode are investigated. Filter tuning, accomplished by adjusting the height of conducting planes above the resonant filter sections, is demonstrated.

[8] Z. Rav-Noy, C.-en Zah, U. Shreter, D. B. Rutledge, T.-C. Wang, S. E. Schwarz, and T. F. Kuech, "Monolithic Schottky Diode Imaging Arrays at 94 GHz," International Conference on Infrared and Millimeter Waves, December 1983, Miami FL.

Abstract - Monolithic GaAs Schottky diode imaging arrays have been demonstrated at 69 and 94 GHz. In the 94 GHz experiments, the diodes are fabricated by a self-aligning technique on semi-insulating GaAs and are isolated by a combination of a mesa-etch process and proton-bombardment. The

series resistance is 20 Ω and the estimated capacitance is 15-20 fF. The antennas are planar bow-ties, and power is coupled in through a quartz lens placed on the back of the GaAs substrate. The wafer is lapped to 90 μm thick to eliminate losses to substrate modes. The measured system responsivity is 330 V/W. The 69 GHz diodes are made by a non-self-aligned process, and a silicon substrate lens is used.

[9] S. E. Schwarz and D. B. Rutledge "Moving Toward Near-Millimeter-Wave Integrated Circuits," *Microwave Journal*, June 1980, pp. 47-52.

Students who have received Ph.D.'s

Chingchi Yao	1983
Nan-lei Wang	1985
Taichi Wang	1984
Gregory S. Lee	1985

Master's Degrees

Tom Reddish	1983
Lauretta Hoberg	1982
Ann Waldhauer	1983

Ph.D. Expected

Dylan F. Williams	1986

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